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PERSPECTIVE

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Potential influences on the United Kingdom's floods of winter 2013/14

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During the winter of 2013/14, much of the UK experienced repeated intense rainfall events and flooding. This had a considerable impact on property and transport infrastructure. A key question is whether the burning of fossil fuels is changing the frequency of extremes, and if so to what extent. We assess the scale of the winter flooding before reviewing a broad range of Earth system drivers affecting UK rainfall. Some drivers can be potentially disregarded for these specific storms whereas others are likely to have increased their risk of occurrence. We discuss the requirements of hydrological models to transform rainfall into river flows and flooding. To determine any general changing flood risk, we argue that accurate modelling needs to capture evolving understanding of UK rainfall interactions with a broad set of factors. This includes changes to multiscale atmospheric, oceanic, solar and sea-ice features, and land-use and demographics. Ensembles of such model simulations may be needed to build probability distributions of extremes for both pre-industrial and contemporary concentration levels of atmospheric greenhouse gases.

Simulations by climate research centres[1] project that raised levels of atmospheric greenhouse gas (GHG) concentrations are changing the climate system. This is detectable in temperature measurements with high statistical confidence[2], and the algorithms leading to this statement pass robustness tests[3]. Simultaneously, there is evidence of a human-induced signal in some impacts, for example major sea-ice reductions[4]. For the UK, recent trends of increasing heavy rainfall events have been observed[5]. Increases in mean mid-latitudinal precipitation, when averaged to latitudinal bands, are sufficiently strong to allow attribution to raised GHG concentrations[6]. An anthropogenic influence has also been detected at high latitudes[7], in seasonal precipitation[8] and in thermodynamic and dynamic precipitation features[9]. Most general circulation models (GCMs) project increased global mean precipitation of order of 1–3% per degree of global warming[10]. Although some robust cross-GCM features exist[11], there are important differences in the spatial patterns of change and even disagreement in sign in some regions, inhibiting attribution statements by comparison with observed precipitation. For the UK, however, over 90% of models in the Fourth Intergovernmental Panel on Climate Change (IPCC) assessment (Figs SPM7 and 10.9 in ref. 12) estimate mean precipitation increases for December–February for the period 2090–2099 under unmitigated emissions. The fifth IPCC assessment additionally reports for 2046–2065 (Fig. 12.22 in ref. 13), showing a multi-model mean precipitation increase. The latter is less than two standard deviations in variability, although at such earlier times signal strengths are smaller. Translating rainfall projections to flood risk, northwest Europe, including the UK, is therefore a region projected to experience increased flood frequency, with a relatively high consistency between GCMs (Fig. 1 in ref. 14).

The high impact of flooding on society has focused attention on rainfall extremes of different durations. A yearly report assesses many observed extremes in the context of background climate variability and change applicable for their location[15]. Over many land regions, including the mid-latitudes, measurements indicate an increasing frequency of intense rainfall events, in agreement with climate model estimates[16]. Additional analysis for 8,000 weather stations indicates trends between 5.9% and 7.7% per degree of warming in annual maximum daily rainfall[17]. For northern latitudes there is some evidence of anthropogenic influence causing rainfall intensification[7] verified by comparing against both simulations[1] of natural variability and simulations including anthropogenic forcing. For the UK, regional climate models (RCMs) project reduced return times for high rainfall events in a warming world[18]. Rainfall intensification is not, however, universal in RCM projections (for example, for parts of the Mediterranean region, the opposite may be true depending on season[19]).

Against a background of evidence of a human influence on the hydrological cycle, we place the December 2013 to February 2014 (DJF1314) UK floods in the context of historical events. We discuss known potential drivers of mid-latitude storm features, before leading to a perspective on what is required to fully understand whether climate change may result in any changed likelihood of DJF1314-type events.

The winter 2013/14 UK floods

DJF1314 witnessed a rapid succession of vigorous Atlantic low-pressure systems crossing much of the UK. In December, associated heavy rainfall, compared with the respective climatology, was observed in two distinct regions of southeast England and most of

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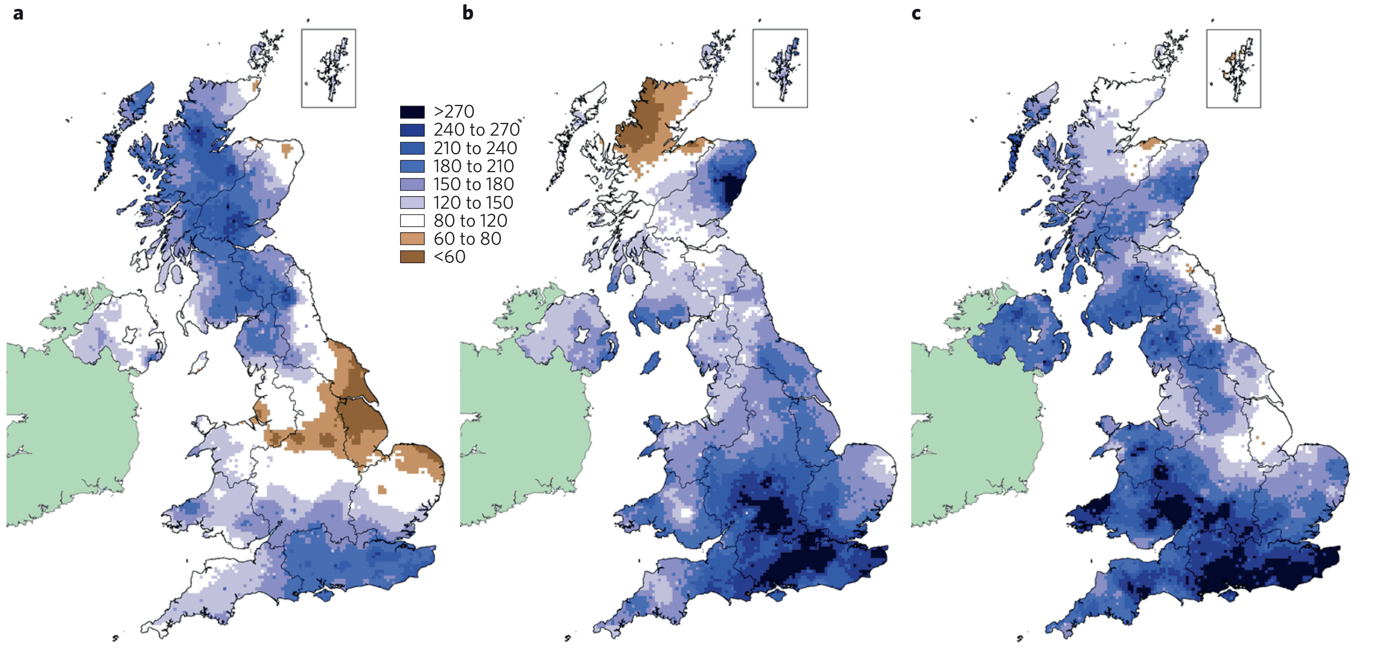

Figure 1 | UK rainfall. a–c, Maps of UK rainfall anomaly as a percentage of 1981–2010 monthly average for December 2013 (**a**), January 2014 (**b**) and February 2014 (**c**).

Scotland (Fig. 1a). Such heavy rain continued in parts of the UK in January and February (Fig. 1b,c). This resulted in sustained high runoff rates and river flows, especially for the southern UK, exacerbated by increasingly saturated catchments. In December 2013, the highest tidal surge since 1953 resulted in widespread coastal flooding, and the storms throughout DJF1314 caused considerable erosion, especially on western coastlines. The saturated ground conditions contributed to cliff failures, landslips and the appearance of sink holes. Although runoff rates tended to decline from mid-February, flows in many groundwater-fed streams and rivers continued to respond to the major winter recharge to aquifers, which outcrop extensively across much of the country.

The River Thames drains the largest catchment in the UK. The gauging station at Kingston in west London has the longest continuous flow record in the National River Flow Archive, beginning in 1883. Flows increased rapidly through December 2013 (Fig. 2a, green curve), and upstream Thames floodplain inundations were extensive and protracted until late-February. In the context of previously recorded seasonal maximum flows (blue curve), December 2013 was a significant peak, followed by even higher peaks in both January and February 2014. During the latter month, naturalized flow (which takes account of the main abstractions upstream of the gauging station) reached 524 $m^3 s^{-1}$ ('cumecs'; red line in Fig. 2b). Although it is the highest flow since 1974, this peak has been exceeded on eight other occasions in the 132-year record (Fig. 2b) with the highest peak recorded in November 1894. Many of these peaks occurred in earlier parts of the time-series when winter temperatures were generally lower. Snowmelt, sometimes over frozen ground, was an aggravating factor in the extensive flooding in March 1947 across England and Wales, and in 1928 it contributed to the last major inundation of central London. Historically, ice-damming behind the many weir structures along the Thames also added significantly to flood risk. In a warming world, snow cover for northern latitudes is generally decreasing[20].

Where the DJF1314 Thames river flow is exceptional is the duration for which daily flow continuously exceeded 250 $m^3 s^{-1}$ (a threshold broadly corresponding to that at which spillage would have occurred in the Kingston reach before the major channel re-profiling following the 1947 flood). During DJF1314 this threshold was exceeded on 76 consecutive days, the previous longest sequence being 30 days (in 1947). Total winter rainfall in the Thames catchment was the highest on record (Fig. 2c). Similarly, sustained high flows were observed across other major rivers in southeast England (DJF1314) and parts of Scotland (December) (Figs 3–5), reflecting high rainfall amounts (Fig. 1). Although extreme peak flows in individual rivers were rare, accumulated runoff totals for DJF1314 exceeded those for any previous 3-month sequence in 31 out of 64 records of national index catchments. For England and Wales as a whole, the DJF1314 total flow was the highest for any three consecutive months, in a record beginning in 1961. Exceptional aquifer recharge occurred, particularly across southern and central England, triggering groundwater flooding in vulnerable areas. All national index wells in the chalk of southern England registered their highest or second highest February levels on record. For Compton in southern England, average borehole levels in January and February 2014 have been exceeded only once, and then only marginally, in a time-series from 1894 (Fig. 2d).

River-flow records show relatively little evidence for long-term increase in UK flood severity[21], although identification of trends can be confounded by dam construction, river engineering, major land-use change and abstractions. To minimize these confounding effects, networks of relatively undisturbed UK catchments with good-quality hydrometric records have been identified. These show some trends[22], notably increases in high-flow frequency and magnitude, particularly in the winter half-year, and for upland areas of the north and west. This is consistent with other studies finding increases in heavy rainfall for those seasons and regions[5,23].

Undisturbed catchments may allow climate-driven trends to be discerned above direct human disturbances, but attribution statements using observed flow remain difficult as records are normally short (most UK river-flow data sets only started in the 1960s) and natural variability is high. Longer records are usually for rivers with some direct human modification of flows. For the Thames, the lack of compelling statistical evidence of an increase in flood magnitude for the period 1883 to 2010 may, in part, reflect more recent lower levels of snowmelt, particularly over frozen ground. In relation to flood risk generally, sustained river management, for example increasing channel capacities and constructing more hydraulically efficient weirs, has certainly been beneficial; there has been a significant decline in annual maximum levels in the Thames since the 1880s[24]. Flood histories for many rivers based on proxies of flood-causing weather types (extending back into the early nineteenth century)[25], or on flood marks and documentary records (extending back to the seventeenth century or earlier)[26], are available. Although partial and uncertain, these indicate a tendency for floods to cluster together in 'flood-rich' and 'flood-poor' periods[22,27]. Such interannual to interdecadal variability may reflect atmospheric circulation drivers. Winter runoff and flood indicators have been linked to the atmospheric North Atlantic Oscillation (NAO) index[22]. The NAO in the 1990s was strongly positive and associated with a cluster of winter flood events, contrasting with the early 1960s for which the index was negative and which were correspondingly flood-poor. Recent major flood events have occurred in the summer half-year, for example in years 2007 and 2012, the latter being the last in a sequence of six summers with June–August rainfall totals exceeding the 1981–2010 average of England and Wales[28]. Other atmospheric and oceanic circulations (for example the Atlantic Multidecadal Oscillation, AMO[29]) may also generate periods spent with raised or lowered rainfall amounts, with time spent in each potentially modified by anthropogenic emissions.

Weather and climate change drivers

For the UK, the single largest indicator of winter atmospheric circulation, including storm track position and strength, is the state of the NAO, characterized as the atmospheric pressure difference between the Azores and Iceland. Although the surface low-pressure anomaly was shifted slightly south, the surface NAO was strongly positive in DJF1314. Modelling and understanding the extreme winter phases of the NAO, and its hemispheric equivalent the Arctic Oscillation (AO)[30], are improving[31]. Coupling of the NAO with the Atlantic Ocean state has been suggested[32], and there is observational and modelling evidence that the AMO switching to a more positive phase over the past 20 years has probably increased the NAO, simultaneously raising northern European rainfall[29]. Climate models now also confirm that the AMO couples to the atmosphere[33], highlighting the requirement for accurate oceanic modelling. Evidence that the interannual variability of the NAO is being influenced by raised atmospheric greenhouse gas concentrations is of particular interest[34], but requires robust characterization compared with natural fluctuations in the NAO.

Particular to DJF1314, the very strong Atlantic jet stream and associated intense UK storms can be partly traced back to rainfall anomalies in the tropics[35] (Fig. 6). Although neither El Niño nor La Niña was active this winter, tropical Pacific rainfall was displaced westwards, with very heavy rainfall over the west Pacific, Indonesia and the eastern Indian Ocean. This can drive high pressure in the northeast Pacific, as occurred in DJF1314 and can force downstream strengthening of the Atlantic jet stream by at least two mechanisms. First, filling the Aleutian Low reduces the amplitude of planetary-scale waves in the upper troposphere[36] and strengthens the stratospheric jet that subsequently strengthens the Atlantic jet stream[37]. Second, intense northerlies over the United States advect cold air southwards over North America, as has occurred in past extremes[38]. This results in strong temperature gradients between North America and the tropical Atlantic Ocean, promoting enhanced storm development[39]. Simultaneous adjustment of westerly winds in the upper troposphere over the East Pacific also created a westerly duct for disturbances to enter the origin of the Atlantic jet stream[40]. This list of connected meteorological events will now be the subject of considerable additional analysis and research. Looking further back to

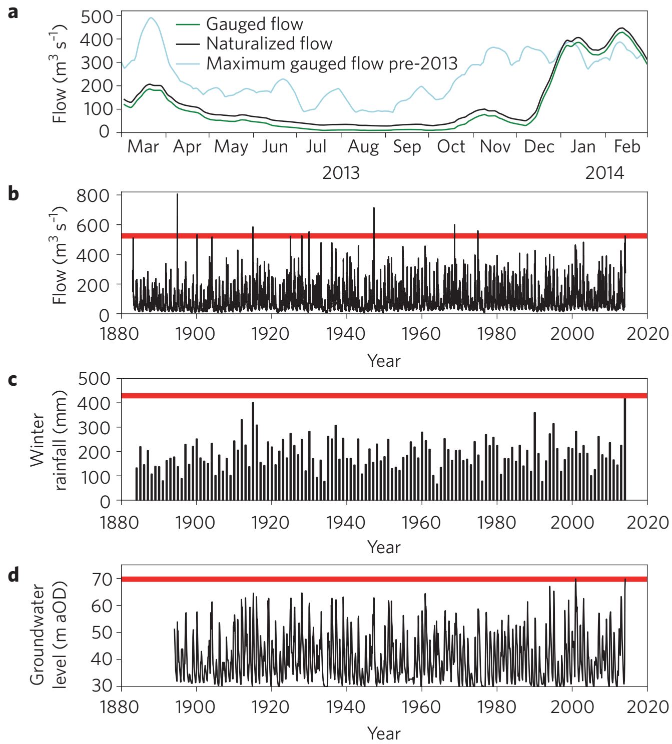

Figure 2 | River flows at Kingston on the River Thames, UK, and associated rainfall and groundwater levels. a, The 21-day centred running means for March 2013 to February 2014 (green curve), along with naturalized estimates (black curve). Historical day-of-year maximum of 21-day running means of gauged flows, between 1883 and December 2012, is the blue curve. **b**, The naturalized daily river-flow time series for 1883 to February 2014. The red horizontal line is the February 2014 peak flow. **c**, Winter (DJF) rainfall totals averaged across a set of rain gauges in the Thames catchment. Red line is DJF1314 value. **d**, Groundwater levels at Compton (metres above Ordnance Datum). Red line is maximum in DJF1314.

events leading to the intense Indonesian heavy rainfall will require a fuller understanding of Pacific Ocean changes in a warming world[41], including the relative roles of greenhouse gases and atmospheric aerosols on tropical circulation and rainfall.

Additionally, there is evidence for an impact of the Quasi-Biennial Oscillation (QBO) on winter surface climate. The QBO occurs through an alternating sequence of easterly and westerly zonal winds in the tropical stratosphere[42]. Although it is remote from the North Atlantic, the QBO affects Atlantic and European climate[43,44] via the stratosphere[45]. Importantly, in DJF1314, the QBO was in a very strong westerly phase, consistent with a strong Atlantic jet stream in DJF1314. The resulting increased pressure gradient in the Atlantic then increased the risk of heavy rainfall in northern Europe[46]. The teleconnection from the westerly QBO signal in the tropics to the extratropical stratosphere and down into the Atlantic region, as typically seen during strong westerly phases of the QBO[42,47], may therefore have exacerbated the excessive winter storminess and rainfall.

Often recently cited as another potential driver of UK winter climate is Arctic sea ice. Paradoxically, warming-induced Arctic sea-ice loss[4] may favour easterly flow and abnormally cold winters over Northern Europe[48,49], such as the winters of 2009/10[50] and 2010/11. Reduced November ice extent in the Kara Sea in particular may be a precursor to negative NAO. However, mid-latitude responses of GCMs that have been run with prescribed Arctic sea-ice reductions vary considerably, some showing a significant winter cooling response over northern continents[51] while others do not[52,53], and for

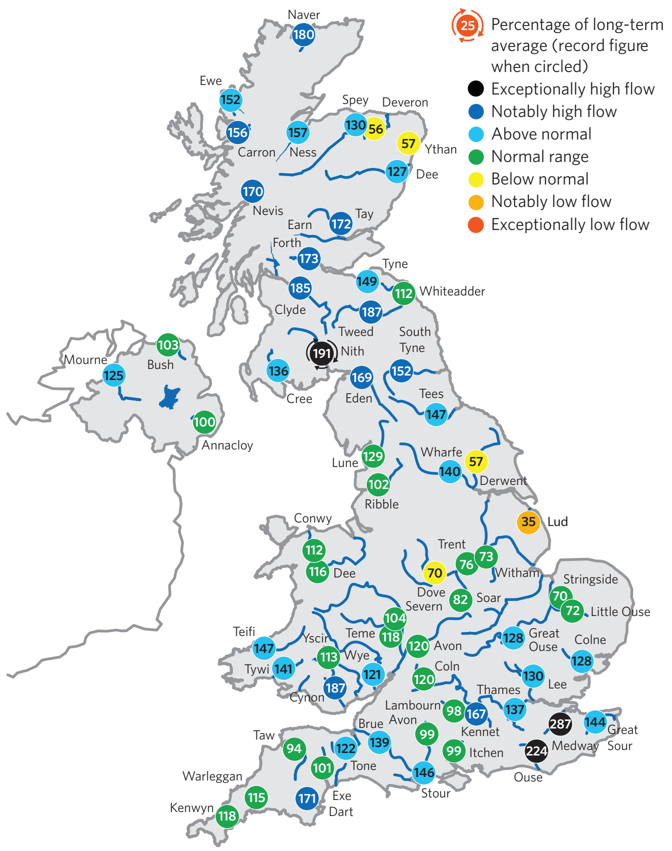

Figure 3 | Monthly river flows for major UK rivers for December 2013. Flows are expressed as a percentage of long-term monthly means (each record at least 30 years).

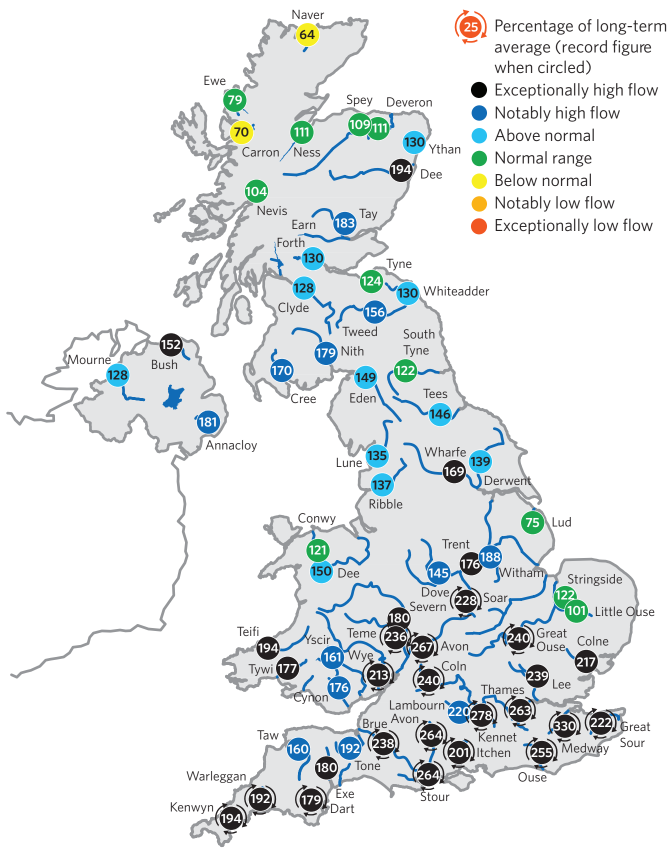

Figure 4 | Monthly river flows for major UK rivers for January 2014. Flows are expressed as a percentage of long-term monthly means (each record at least 30 years).

present day there are difficulties in separating the impacts of sea-ice loss from large natural variability[52]. The UK events of DJF1314 were, though, dominated by warm westerly winds. Disproportionately large Arctic warming may also weaken the jet stream through decreased north–south near-surface temperature gradients, potentially causing it to have larger north–south meanders[54]. This could increase the likelihood of high-impact weather extremes such as cold waves, perhaps by slowing weather system progression and increasing the frequency of blocking events. Robust observational evidence for wave amplitude increases[55,56], or blocking, is currently lacking[57] however, and the DJF1314 storms were tightly coupled to a very strong Atlantic jet stream.

Finally, solar activity may also affect regional climate variability. Palaeoclimate studies, based on analysing the growth of speleothems in caves geographically close to large spatial gradients of average rainfall[58], indicate that solar activity can influence rainfall. Since 1985, average solar activity levels have declined steadily, generating discussion of the impact on global and regional surface temperatures[59], but there is little consensus on its impact on precipitation. Forecasts based on how cosmogenic isotopes have varied in the past in situations analogous to today indicate[60] a probability of order 10% that the Sun will return to the conditions of the Maunder Minimum (approximately 1650–1710) within the next 40 years. Consideration of the rapidity of the current decline increases that probability to nearer 20%[61], but even these extreme solar changes are predicted to have relatively minor effects on global mean climate[3,62]. Solar influences may, however, adjust the jet stream and thus European winter rainfall through modulation of the latitudinal distribution of stratospheric heating. Solar influence on cold European winters, via increased occurrence of blocking events, has been inferred from observation reanalysis data[63], and detected in pre-satellite meteorological data[64], including the Central England Temperature record[65]. Models including the stratosphere are also starting to reproduce this signal and agree with proposed explanations of the effect[66]. The consequences for European precipitation remains uncertain, but palaeoclimate signatures exist, for example, in Alpine speleothems[67] and snow-fed springtime flooding[68]. Low solar activity would be likely to decrease future UK winter precipitation if it induced persistent blocking resulting in cold dry easterlies. Although this is opposite to features of DJF1314, we are just leaving behind a weak solar maximum. Hence, although solar effects may be minimal on DJF1314 events, stratosphere-resolving models will be required to understand their role among a range of forcings.

Issues of atmospheric model resolution

Advances in model dynamics[69] and resolution mean that UK weather forecasts now have levels of accuracy five days ahead that were only possible two days ahead just 25 years ago[70]. It is argued that advances in long-range forecast reliability should also apply to longer-term climate projections[71], subject to the processes being similar in both applications[72]. The UK Met Office uses a common dynamical core for weather forecasting, seasonal prediction and climate change projections. This 'seamless prediction'[71] allows understanding of the causes of those common model biases that often appear within the first few days of simulation, potentially leading to improved process representation and bias removal in subsequent models.

GCMs aim to represent variability in large atmospheric circulation patterns, including the drivers discussed above. High-resolution versions of GCMs, with grid spacings of 20–60 km, are currently being developed. At such resolutions, these models give a better representation of the large-scale drivers, such as storm tracks and embedded depressions, that are key to representing events such as those witnessed in DJF1314. Persistent anticyclonic blocking is typically under-represented in GCMs[73], affecting mid-latitude flow with implications for UK rainfall projections, but this may be improved in the Atlantic sector with increases in model resolution or other changes that remove key biases[74].

Furthermore, RCMs are often nested within GCMs to provide high-resolution information over a region of interest. Such models have typical resolutions of 10–50 km and give an improved representation of daily rainfall extremes. But considerable variation exists between different RCMs' downscaling of the same large-scale features to estimate extreme precipitation[75]. RCMs with kilometre-scale grid spacing (convection-permitting resolution) are also now available. These very high resolutions are too computationally expensive for global operation, but applied regionally they give improved representation of local rainfall processes. Climate change experiments have recently been completed at 1.5-km resolution for the southern UK[76], showing heavier downpours in the future with global warming. This model gives better representation of various aspects of duration and spatial extent of rainfall[77] and more realistic hourly extremes[78] than coarser-resolution climate models. Many improvements are linked to the explicit (non-parameterized) representation of convection[77]. Thus the benefits of such resolutions are expected to be greatest in summer when convective storms are most prevalent. Hence, although summer downpours can only be described accurately at convection-permitting scales, changes in UK winter rainfall seem robust when changing from 12-km to 1.5-km resolution[76]. DJF1314 heavy rainfall was a sequence of frontal storm occurrences and so it remains an active area of research to understand resolution benefits for larger storms of this type.

Very-high-resolution RCMs can provide benefits in terms of assessing the consequences of heavy rainfall, such as in DJF1314, for flooding. Ensembles of RCM models are used to drive flood estimate models[79], but at typical RCM grid-scale additional spatial downscaling is needed[80]. Very-high-resolution RCMs remove the need for additional spatial disaggregation of outputs and provide realistic fine-scale spatial and temporal rainfall information that can be used directly to drive river-flow models.

Hydrological modelling

Seamless projection for end-to-end attribution[81] of flood risk (combining probability and consequence of flood occurrence) implies routine coupling of climate projections with detailed models of river flow and flood extents, including interaction with flood defences and socio-economic details of properties and businesses. Modelling the potential increase in flood risk for Europe by the 2050s suggests that economic losses could increase from an estimated 4.2 billion euros per year in the 2000–2012 period, to 23.5 billion in the 2050s, under a business-as-usual emissions scenario[82]. Interestingly, the bulk of the increase (about two-thirds) could be due to socio-economic development rather than climate change itself[82]. Hydrological models must represent many factors affecting the transformation of rainfall to river flows, including geology, soils and land-use. For the Thames Basin, a 1-km gridded hydrological model (Grid-to-Grid) forced by several 25-km-grid regional climate models from UKCP09 shows an ensemble-mean increase in flood peaks by the 2080s[79]. But considerable variation exists between the 11 ensemble members, with large spatial variations related to catchment properties. At some locations, some ensemble members show increases beyond the range of natural variability. More recent work has taken a bottom-up approach to the impacts of climate change on flooding in Britain, by using hydrological modelling to establish categories of rainfall-to-flood peak response, linked to catchment properties and underlying climate[83,84]. Of 1,120 gauged catchments in England and Wales,

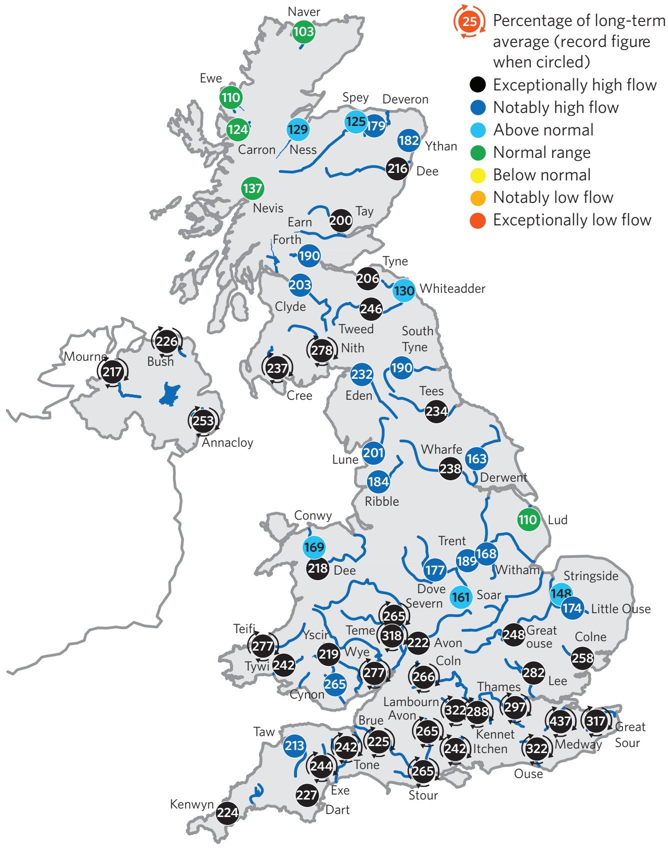

Figure 5 | Monthly river flows for major UK rivers for February 2014. Flows are expressed as a percentage of long-term monthly means (each record at least 30 years).

35% are categorized as having an enhanced flood response to rainfall changes[85]. That is, any increase in winter monthly rainfall would generate a proportionately larger increase in flood peaks. Catchments in Britain are most sensitive in autumn and winter[86] when rain falls onto ground generally more saturated owing to less evaporation of soil moisture.

Changes in land use may adjust surface hydrological characteristics, such as infiltration and soil storage, affecting the timing and magnitude of flood response downstream[87]. The effectiveness of flood prevention by increased upland storage (for example, farm reservoirs, wetlands, floodplains) and changes to crop type therefore requires assessment. For the most extreme rainfall totals, these measures may dampen peak flows but not completely remove flood risk; evidence of land-use management impact on catchments larger than 10 km^2 remains elusive[88]. Although much of the recent UK flooding was in rural areas, the influence of urbanization requires appraisal, particularly given pressures to build on floodplains. Responses to rainfall extremes in urban areas are faster than for natural surfaces (affecting fluvial and pluvial flood risk)[89], but can be partially mitigated by detention ponds, soakaways, permeable concrete and provision of vegetated areas.

Damage to exposed European coastal assets from raised sea levels and storm surges could cost tens of billions of euros per year without adaptation[90]. Of the mechanisms involved, the most damaging is often the flood component from short-lived storm surges, where low atmospheric pressure and strong winds add to tidal levels, causing extreme coastal water levels. The great flood of 1953, resulting from a large storm surge event on an already high tidal level, caused considerable loss of life in the UK and Netherlands, and ultimately led to the construction of the Thames

Box 1 | Summary of the four main types of flooding that can occur.

Flooding may be regarding as falling into the following four broad categories.

Fluvial flooding involves flow in rivers either exceeding the capacity of the river channel or breaking through the river banks, and so inundating the floodplain. A complex set of processes is involved in the translation of precipitation into runoff and subsequently river flow (routing of runoff along river channels). Some of the factors involved are the partitioning of precipitation into rainfall and snowfall, soil type, antecedent soil moisture, infiltration, land cover, evaporation and plant transpiration, topography and groundwater storage. Determining whether a given river flow exceeds the channel capacity, and where any excess flow will go, is also not always straightforward and is complicated by the presence of artificial river embankments and other man-made structures.

Pluvial flooding can be defined as flooding derived directly from heavy rainfall, which results in overland flow if it either is unable to soak into the ground or exceeds the capacity of artificial drainage systems. Pluvial flooding can occur far from river channels and is usually caused by high-intensity, short-duration rainfall events, although it can in some circumstances be caused by lower-intensity, longer-duration events, or by snowmelt. Other factors influencing pluvial flooding include soil type, antecedent soil moisture, land cover (especially urbanization), and capacity and maintenance of artificial drainage systems. Both pluvial and fluvial flooding can potentially result from the same rainfall event.

Groundwater flooding tends to occur in areas underlain by permeable rocks, where sustained periods of heavy rainfall can cause the water table to rise above ground level. There can also be a significant groundwater component to fluvial flooding, in rivers where a high proportion of the flow can come from groundwater sources (aquifers). When groundwater flooding occurs it can last considerably longer than either fluvial or pluvial flooding, and thus cause greater difficulties for affected communities.

Coastal flooding involves the sea inundating part of the land beyond the normal tidal range, and is typically associated with the occurrence of a storm surge. Such events are driven by low atmospheric pressure over the sea and strong winds whose direction is such that they tend to drive more water towards the coast. Over time the surge will progress along the coastline so that at a single location it typically lasts a few hours. Sometimes the movement of the atmospheric storm can be such that it increases the surge magnitude as it progresses along the coast. The largest flood events typically correspond to a large surge occurring on the rising limb of the tidal cycle. Strong winds can also cause large waves, which can overtop some flood defences and further increase damage.

Barrier. Changes in extreme sea levels around the world have been dominated by variation in local mean sea level[91]. Focusing on the UK coastline, UKCP09 RCM projections[92] indicate that major changes in storm-driven surge frequency are unlikely over the coming decades. However, a robust projection is that the time-mean sea level, globally and around the UK, is expected to continue to rise over the next century and beyond, increasing the height of extremes, and continuing even after any climate stabilization[93]. Recent estimates[94] suggest that the frequency of extreme events around the UK, resulting from increases in time-mean sea-level rise, can be expected to increase by a factor of more than 10 at many locations, and at some locations by more than 100 over the next century. This applies both to the moderate extremes at lower return periods, such as the annual maximum water level, and to the often much more damaging 1-in-100-year events. Capability is increasing to alert to the risk of surges more days in advance, using predictions of wind and pressure fields along with models of potential inundation extent, interaction with flood defences and ongoing better representation of coastal topography.

Fractional attributable risk

An overarching statistic to evaluate the combined impact of all potential changing drivers due to increasing atmospheric greenhouse gas concentrations is the fractional attributable risk (FAR)[95], which quantifies the extent to which anthropogenic emissions have increased, decreased or not altered the likelihood of an observed sequence of intense weather events. FAR = $1 - R_N/R$, where R is the expected occurrence-frequency of an event above a threshold of concern that can be expected for current GHG concentrations, and R_N is an estimate of this number for conditions had climate not been affected by anthropogenic emissions. One method of deriving the FAR requires populating statistical distributions for R and R_N with ensembles of GCM simulations, so far generated with seasonal forecast atmosphere-only models[96,97], and as a citizen science experiment on personal computers to generate very large ensembles[96,98]. At higher resolutions, this may represent a challenge for emerging cloud computing services, including issues of parallelization and data transfer. Evidence of sea ice, ocean and stratosphere behaviours (among others) influencing UK rainfall patterns also raises computational requirements to include these components. Long simulations may be needed to understand frequency changes in oceanic states such as the AMO with and without anthropogenic intervention.

The one FAR study so far to focus on heavy seasonal rainfall in the UK[96] found an increase of around 10% in the intensity of relatively infrequent runoff events as a result of past GHG emissions, and under the specific conditions corresponding to those that occurred in autumn 2000. This gives a corresponding reduction in return period of about 50%, or a FAR of 0.5, but with a large range of uncertainty. The FAR has been estimated for peak flows for England during the same period[99], similarly indicating that for most catchments modelled, raised greenhouse gases have led to a greater probability of high flows. Such analysis[99] extended to cover winter months found FAR increases moderated by reduced probability of major snowmelt. Pall *et al.* noted[96] that rainfall change was broadly consistent with simple thermodynamic arguments raising atmospheric water-holding capacity for the warming attributable to GHG emissions so far. However, they[96] recognize any major circulation changes, caused by altered GHG concentrations, as a potential strong modulating factor to this argument. Although background thermodynamic considerations would also apply to DJF1314, the global atmospheric circulation picture, as outlined above, was especially different from autumn 2000. This needs to be incorporated in any FAR calculation for these more recent rainfall events.

Discussion

During DJF1314, the UK experienced pluvial, fluvial, tidal and groundwater floods (Box 1). Maximum peak flows were generally not record-breaking, but sustained high flow levels occurred as a consequence of repeated heavy rainfall events. In general, fluvial and tidal flood defences protected properties, although

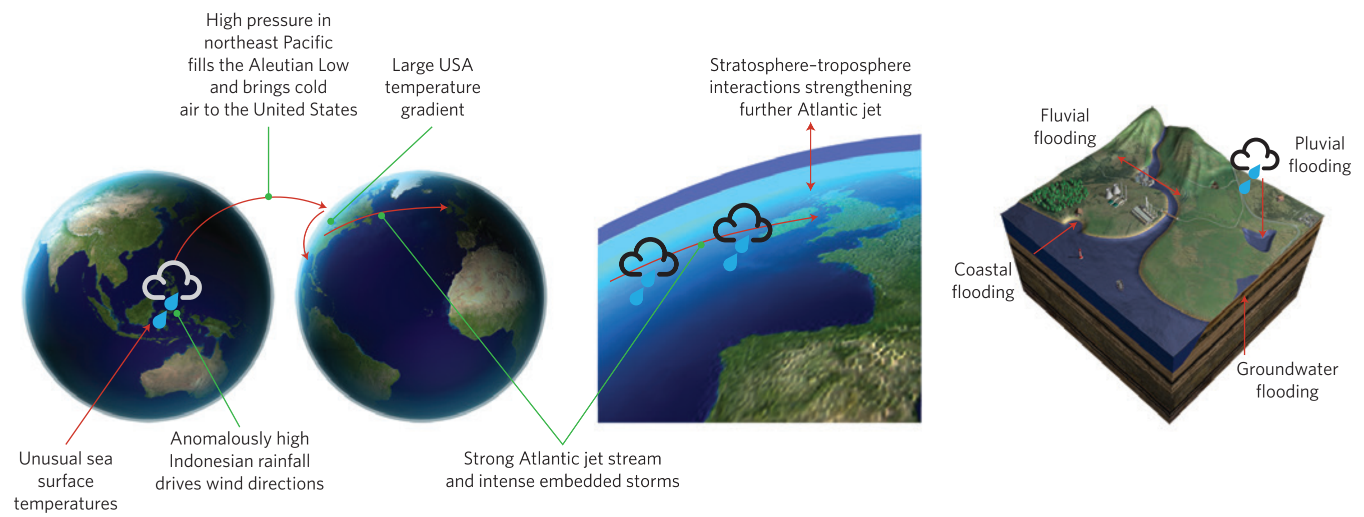

Figure 6 | Schematic of potential flood drivers. A diagram of forcings believed to have influenced the winter 2013/14 UK floods.

transport disruption was considerable and floodplain inundation affected low-lying communities severely. An early report[35] suggests a chain of events (Fig. 6) where Pacific tropical rainfall and circulation were conducive to increased UK storminess. We have explored this and a broad range of other drivers. Inevitably, questions are asked as to whether anthropogenic emissions of greenhouse gases were a factor. The definitive answer will depend on any combined changes to a large number of connected features of the climate system. The role of anthropogenic aerosol effects requires further work, especially on tropical atmospheric circulation and hence rainfall, given high regional variations in concentration of aerosols compared with well-mixed GHGs. We note that both the tropical Pacific and tropical stratosphere were probably involved through established teleconnections to North America and the Atlantic. It is also notable that sea-ice decrease and solar activity, two often-cited drivers of mid-latitude weather systems, seem unlikely to have affected the particular DJF1314 rainfall characteristics.

Calculating the FAR of DJF1314 rainfall events to anthropogenic emissions will provide a single statistic that captures overall change. This could aid adaptation planning, and, if positive, provide a means to relate emissions to monetary damages. It allows progress from the statement that no meteorological or hydrological extreme can be unequivocally attributed to climate change, to a situation where the potential size of the effect can be stated. FAR calculation provides three challenges for coupled GCM-modelling. First, we need the simulation of ocean circulations (in particular Pacific sea surface temperatures for DJF1314-type events), sea-level height, atmosphere, cryosphere and their interactions, all to a high degree of fidelity. Significant uncertainty in the FAR is related to the set-up of the modelled non-industrial climate, and when applied to flood response, to uncertainty in evaporation estimation, hydrological model structure and parameterization. Second, describing the response of fine-scale storm features to these large-scale drivers may require step-changes in model resolution. Third, as weather extremes are by definition rare, this makes extraction of signal from variability sometimes difficult. Populating the statistical distributions for the FAR therefore demands large numbers of modelled representative years for both non-industrial and industrial GHG concentrations. However, we gain much encouragement from looking at progress so far. Generally heavier precipitation due to thermodynamic effects of atmospheric warming is known from theoretical viewpoints, and is a robust feature of GCMs for many regions[100]. River-flow models include local influences of river management, land-use changes and abstractions, allowing their effect to be seen in parallel with any climate change factors. Very high-resolution atmospheric models are being tested, and new computational resources are being harnessed to perform large ensembles. To refine projections and FAR estimates, debate is required as to how best to divide research resource between further building our understanding of processes, model development including appropriate resolution, and ensemble size.

Besides modelling strategies, the importance of observational data sets should be reiterated. Historical data provide crucial quantification of past variability and extremes, and a test for GCMs to reproduce past climate. Comprehensive benchmark monitoring networks need development and maintenance, along with further proxy indicators of flood occurrence over past centuries. Specifically, data can refine the determination of flood-generating thresholds. These include quantifying the frequency of rainfall of sufficient intensity to cause pluvial flooding, of accumulation large enough to cause fluvial floodplain inundation, or of exceptional winter rainfall totals sufficient to create major groundwater flooding. Any expected changing probabilities of rainfall crossing such thresholds then require calculation, including any altered risk of joint occurrence of flood types.

Although there is some observational evidence of intensification of UK rainfall, there is little suggestion of emerging trends in precipitation-driven (that is, non-tidal) high-magnitude UK floods; less UK ice and snowmelt in a warming world may suppress flood risk. A lack of trends cannot, however, be taken to mean there is no underlying emerging climate change signal, given the low signal-to-noise ratio in flood records. Accurate FAR calculation for rainfall or flood extremes such as occurred in DJF1314 is required, summarizing the influence of raised atmospheric GHG concentrations on the many potential drivers identified. Should the FAR value be positive, it could be used to inform planning decisions to better manage any more frequent flooding due to climate change. This can then be interpreted in the context of other modulating factors, such as land-use change.

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Author contributions

C.H. conceived and designed the paper. T.M., J.H. and S.P. provided hydrological data and their interpretation. T.L. provided rainfall data. Latest research understanding was provided by A.A.S., E.J.K., J.S. and M.R. on high-resolution atmospheric modelling and processes; by A.L.K., C.P., V.A.B. and N.S.R. on flood modelling and processes; by M.L. and A.A.S. on solar–climate interactions; by J.A.L. on issues of sea-level rise and coastal flooding; by J.A.S. on sea-ice–climate interactions; by P.A.S. on rainfall trend detection and attribution; and by F.E.L.O., N.M. and M.R.A. on the fractional attributable risk statistic and large ensemble modelling. C.H., H.C.W., M.B., N.S. and A.J. discussed the overall aims of the paper. All authors contributed to the writing of the paper.

Additional information

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Competing financial interests

The authors declare no competing financial interests.